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THE LYMAN-ALPHA FOREST: A COSMIC GOLD MINE

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ABSTRACT. In recent years, a remarkably simple physical picture of the Lyman-alpha forest has emerged, which allows detailed predictions to be made and turns the forest into a powerful probe of cosmology. We point out ways in which such a picture can be tested observationally, and explore three areas in which the Lyman-alpha forest can yield valuable constraints: the reionization history, the primordial mass power spectrum and the cosmological constant or its variants. The possibility of combining with other high redshift observations, such as the Lyman-break galaxy surveys, to provide consistency checks and complementary information is also discussed.

1 Introduction

The Lyα forest was predicted and observed in the 60s (Gunn & Peterson 1965, Bahcall & Salpeter 1965, Lynds & Stockton 1966, Burbidge et al. 1966, Kinman 1966; see Rauch 1998 for further ref.). Since then, there have been many attempts to place the study of the forest within the framework of cosmological structure formation theories (e.g. Doroshkevich & Shandarin 1980, Rees 1986, Bond et al. 1988, McGill 1990, Bi et al. 1992). Recent numerical simulations lent support to some of these ideas, while clarifying the nature of the forest and allowing detailed predictions to be made (e.g. Cen et al. 1994, Hernquist et al. 1995, Zhang et al. 1995, Petitjean et al. 1995, Miralda-Escudé et al. 1996, Bond & Wadsley 1997, Theuns et al. 1998). We explain in this contribution the physical picture of the forest that has emerged from these and other semi-analytical work (§2), discuss observational tests of this picture (§4), and point out three examples of how such a picture allows us to "mine" valuable cosmological information from the forest (§3).

2 Simplicity of the Forest

Numerical simulations indicate that the low column-density ($N_{\rm HI} \lesssim 10^{14.5} {\rm cm}^{-2}$) Ly$\alpha$ forest (for redshift $z \gtrsim 2$), which occupies a large fraction of any given quasar absorption spectrum, arises from density (and velocity) fluctuations of a smooth intergalactic medium. Regions of enhanced density (in redshift-space) in this smoothly fluctuating medium naturally suffers stronger absorption, creating features like absorption lines, which cannot necessarily be interpreted as due to discrete, well-isolated clouds, as in traditional theories.

The dynamics of such a medium is simple: gravitational instability on large scales, and smoothing due to finite gas-pressure on small scales (Reisenegger & Miralda-Escudé 1995, Bi & Davidsen 1997, Hui, Gnedin & Zhang 1997). Hence, the dark matter and baryon components trace each other on large scales. The fluctuations giving rise to the low $N_{\rm HI}$ forest are mildly non-linear, with the overdensity $\delta\rho/\bar\rho \lesssim 5$, where ρ is the baryon density and $\bar\rho$ its mean. The thermodynamics is well-understood. Shock-heating is minimal and a tight temperature-density relation exists as a result of three processes, recombination cooling, photoionization heating and adiabatic heating/cooling: $T = T_0 \rho^{\gamma-1}$ where T_0 and γ depend on reionization history.

The optical depth τ, which is related to the probability of transmission (f) by $f = \exp[-\tau]$, is (e.g. Hui, Gnedin & Zhang 1997)

$$\tau(u_0) = \int A\rho^\alpha(x) W[u(x) - u_0] dx \quad (1)$$

where u_0 is the velocity of observation, x is the comoving distance along the line of sight, u is the total (Hubble plus peculiar) velocity as a function of position, and W is the Voigt-profile given by $W[\Delta u] = (\pi b_T^2)^{-0.5}\exp[-\Delta u^2/b_T^2]$ with $b_T = \sqrt{2k_B T/m_p}$ where k_B is the Boltzman constant and m_p is the proton mass. The neutral hydrogen (which is what causes the Lyα absorption) density is related to the baryon density ρ by $A\rho^\alpha$, where $1.6 \lesssim \alpha \lesssim 1.8$ for reasonable reionization histories (Croft et al. 1997, Hui & Gnedin 1997). The constant A depends on a number of parameters, among them the cosmological mean baryon density, and the ionization background intensity J whose size is uncertain by an order of magnitude observationally.

To predict the observational properties of the forest, all one needs to know are then **I.** the density and velocity distributions of the gas, which can be obtained by hydrodynamic simulations (ref. in §1), analytical/semi-analytical approximations made possible by the mild nonlinearity of the fluctuations (e.g. Reisenegger & Miralda-Escudé 1995, Bi & Davidsen 1997, Gnedin & Hui 1996, Hui et al. 1997) or alternative efficient numerical techniques (e.g. Gnedin & Hui 1998 [1], Croft et al. 1998); **II.** the temperature-density relation which can be obtained using semi-analytical methods (Hui & Gnedin 1997); **III.** the constant A, which can be fixed by matching the theoretical mean transmission with the observed one (Croft et al. 1998).

Lastly, a few words on the higher column-density absorption systems: they are likely to arise from more nonlinear objects such as collapsed halos or galaxies. Such objects seem to dominate the absorption spectra at low redshifts ($z \lesssim 1$) (e.g. Lanzetta et al. 1995), but not at higher redshifts (see Rauch 1998 for a review).

[1] A regular Particle-Mesh N-body code can be modified to compute the effective potential due to pressure in addition to the usual gravitational potential, taking advantage of the known temperature-density relation.

3 The Cosmic Gold Mine

3.1 Reionization History

Here we explore some effects of the reionization history on a particular statistic called the b-distribution, which has been measured by several groups (e.g. Hu et al. 1995, Lu et al. 1996, Kirkman & Tytler 1997). The b-parameter refers to the width of a Voigt-profile-fit of an absorption line. The number of lines as a function of width is then the b-distribution. The picture outlined in §2 provides a simple interpretation of the measured widths. According to eq. (1), a peak of ρ^α in velocity-space which is narrower than the thermal broadening width b_T will appear as a peak of τ with the shape of a Voigt-profile and a width of b_T. Hence, the measured b-parameter provides a direct indication of the temperature of the gas. On the other hand, structure formation theories predict and allow large-scale fluctuations where a peak of ρ^α is much wider than the local b_T, which means according to eq. (1) the corresponding peak in τ is no longer given by a Voigt-profile shape and its width reflects more the scale of the fluctuation rather than the temperature of the gas i.e. the measured b can no longer be equated with the thermal broadening width.

In more quantitative terms, we can always perform the following expansion around a given absorption peak:

$$\begin{aligned} \tau(u) &= \exp\left[\ln \tau(u)\right] \qquad (2) \\ &\sim \tau(u_{\rm p}) \exp\left[\frac{1}{2}[\ln \tau]''(u-u_{\rm p})^2\right] , \end{aligned}$$

where $u_{\rm p}$ is the velocity coordinate of the line center, and the prime denotes differentiation with respect to u and the second derivative is evaluated at $u_{\rm p}$. The first derivative vanishes because τ is at a local extremum. This expansion gives none other than the Voigt profile itself: $\propto \exp[-(u-u_{\rm p})^2/b^2]$. Hence, the fitted b-parameter would be $b = \sqrt{-2/[\ln\tau]''}$. Assuming most fitted-absorption lines do arise from peaks in τ, and assuming $\ln\tau$ is Gaussian random (as in the case of linear fluctuations, or in the lognormal model), it can be shown that the normalized distribution of lines is given by (Hui

& Rutledge 1997)

$$dN/db = 4(b_\sigma^4/b^5)\exp[-b_\sigma^4/b^4] \quad (3)$$

where $b_\sigma^4 = 2/\langle([\ln\tau]'')^2\rangle$ and $\langle\rangle$ refers to ensemble-averaging. This model naturally explains the salient features of the observed b-distribution: a sharp lower cut-off and a long high-b tail, which could be hard to explain in traditional theories of the forest (see Fig. 18 of Bryan et al. 1998 for a comparison of the above dN/db with observations). In other words, high-b-peaks correspond to gentle fluctuations which are unsuppressed (hence the long tail), while low-b-peaks are sharp fluctuations which are statistically rare.

This model also tells us what determines the b-distribution, through the parameter b_σ: **I.** the (dimensionless) average amplitude of the fluctuations (how nonlinear the field is; see below), and **II.** the three smoothing scales in the problem: the observation resolution, the average thermal broadening scale and the baryon-smoothing-scale due to finite gas pressure; for high-quality Keck spectra, the first is probably negligible, while the latter two are comparable.

How do the thermal broadening scale and the baryon-smoothing-scale change with reionization history? For a fixed redshift of observation (say $z = 3$), as one raises the redshift of reionization, the temperature at $z = 3$ becomes lower (Hui & Gnedin 1997)[2] and the thermal broadening scale becomes smaller. The effect on the baryon-smoothing-scale is more subtle. It is true that the Jeans scale, like the thermal broadening scale, is proportional to $\sqrt{T}$, and so lowering the temperature lowers both. However, as shown by Gnedin & Hui (1998), the true baryon-smoothing-scale is in fact not given by the Jeans scale, but generally given by something smaller. In fact, right before reionization occurs, the baryon-smoothing-scale is very small, and afterwards, the baryon-smoothing-scale does not suddenly jump up to the conventional Jeans scale, but only slowly catches up with it. This means that raising the redshift of reionization could have the opposite effect of allowing a *larger* baryon-smoothing-scale by allowing more time for it to catch up with the Jeans scale. Therefore, exactly how raising the redshift of reionization affects the b-distribution requires a detailed calculation.

This is a subject of much current interest, particularly because of the work of Bryan et al. (1998) (see also Haehnelt & Steinmetz 1998, Theuns et al. 1998) who, after carefully investigating the effect of numerical resolution and box-size on the b-distribution, found that the canonical $\sigma_8 = 0.7$ SCDM model predicts a b-distribution that has too many narrow lines than is observed, if the universe reionizes by $z \sim 6$. The interesting questions are: **I.** changing the fluctuation amplitude will likely shift the b-distribution, but which way will it go? - the arguments leading to eq. (3) indicate that lowering the amplitude would move the b's up (because lowering the amplitude means more suppression of sharp fluctuations or narrow lines), but as pointed out by Hui & Rutledge (1998), nonlinear corrections could reverse this trend; **II.** reionization history will no doubt affect the b-distribution, but as pointed out above, which direction it will go is not obvious and requires a detailed calculation; **III.** as noted by Hui & Gnedin (1997), the mean temperature of the intergalactic medium increases with Ω_b (see also Bryan et al. 1998) and decreases with Ω_m; it would be interesting to see whether changing these would fix the discrepancy of Bryan et al..

It is clear from the above discussion that the inference on reionization history from the b-distribution will depend on assumptions made about the cosmological density parameters and the power spectrum normalization. To isolate the effect of reionization history from the effect of power spectrum normalization, one possibility is to consider the lowest b's, which according to our picture, should correspond to the minimum size imposed by either the thermal-broadening scale, or the baryon-smoothing-scale. However, one should keep in mind the

[2] T is quite independent of $J_{\rm HI}$ as long as H is sufficiently ionized, but does depend somewhat on $J_{\rm HeII}$.

possible complication that not all fitted absorption-lines arise from peaks in τ, e.g. some narrow lines might be introduced to "fill in" the wings of absorption peaks which do not necessarily have Voigt-profile shapes, in which case the physical meaning of the widths of these lines is unclear. One should check for this possibility using simulations, or even develop other characterizations of the line-width which are less prone to systematics of this sort.

3.2 The Primordial Mass Power Spectrum

This is an area pioneered by Croft et al. (1998), who showed that the linear mass power spectrum can be reliably recovered from the power spectrum of the transmission. The idea works as follows. The transmission power spectrum P^f along the line of sight and the three-dimensional mass power spectrum P^ρ are related to each other on large scales by (Hui 1998):

$$P^f(k_\parallel) = \int_{k_\parallel}^\infty BW(k_\parallel, k)P^\rho(k)kdk \quad (4)$$

where P^f is the fourier transform of the two-point correlation $\langle\delta_f(0)\delta_f(u)\rangle$ ($\delta_f = (f-\bar{f})/\bar{f}$ where $\bar{f}$ is the mean transmission), $k_\parallel$ is the velocity-wave-vector along the line of sight and k is the magnitude of the corresponding three-dimensional wave-vector. The kernel $W(k_\parallel, k)$ describes the redshift-distortion of the power spectrum. B is a constant which is determined by the nonlinear transformation from density to the transmission $\exp(-\tau)$ (eq. [1]). Fortunately, the only free-parameter that enters into the determination of the constant B is the constant A in eq. (1) which can be fixed by matching e.g. the observed mean transmission (Croft et al. 1998). It is important to realize that we have made use of the facts that α has a small range (eq. [1]; §2), that the uncertain thermal-broadening and baryon-smoothing-scales only affect the transmission correlation on small scales, and that the dark matter and baryon distributions trace each other on large scales.

It is expected eq. (4) holds on large scales with P^ρ being the linear power spectrum. Hence, once the distortion kernel is fixed (which is predicted by gravitational instability, with dependence on the cosmological density parameters Ω's), the primordial mass power spectrum can be recovered from $P^f(k)$ by inverting an essentially triangular matrix proportional to the distortion kernel (Hui 1998).

There are two main advantages of this way of measuring the linear mass power spectrum. First, unlike in the case of galaxies, the "biasing" relation between density and the observable (the transmission) is known exactly here (aside from the parameter A which can be fixed using independent observations). Second, this provides a direct probe of the linear mass power spectrum on small scales ($k \lesssim 0.02$s/km $\sim 4h\sqrt{\Omega_m}$Mpc^{-1}, for $z \sim 3$; see Croft et al. 1998), which are out of the reach of galaxy surveys at low redshifts (unless one corrects for the nonlinear evolution). This is simply because the nonlinear scale becomes smaller at higher redshifts.

Exciting (and beautiful!) first results of the application of the above techniques to the observed forest were reported recently by Croft et al. (1998b), Weinberg et al. (1998) (see also contribution to this volume by Weinberg). Here, let us list a few issues that deserve some thought and perhaps further investigation. **I.** The distortion kernel W above can be predicted using linear theory, but it is quite possible that the highly nonlinear transformation from the density to the transmission will alter its behavior, even at very large scales (McDonald & Miralda-Escudé 1998, Hui 1998). This should be carefully checked using simulations. **II.** There is an upper limit to the scale above which we cannot reliably recover the mass power spectrum. It is set by the continuum, which is known to have long range fluctuations, and which can only be estimated up to a limited accuracy. This limit is around $k \sim 0.002$s/km, but should be checked carefully using high resolution observations. **III.** The whole inversion procedure discussed above relies on the fact that eq. (1) holds for most of any quasar spectrum, aside from regions of strong absorption such as those caused by collapsed halos. It would be useful to have an estimate of how such regions affect the recovery procedure. **IV.** Numerical simulations are typically used to effectively fix the constant B in eq. (4). It will be useful to have a study of the minimal box-size and resolution required for the problem at hand. For instance, while one expects that resolution can be sacrificed as long as one is interested in large scale fluctuations, resolution does affect the fixing of the amplitude A using the observed mean transmission (Croft, priv. comm.). Analytical methods to fix B would be very useful. **V.** The temperature-density relation mentioned in §2 is expected to have a scatter. It would be good to have an idea by how much it could modify the transmission power spectrum, or in other words, the "biasing" relation between density and transmission.

3.3 The Cosmological Energy Contents

Here, we discuss a version of a test proposed by Alcock & Paczyński (1979; AP hereafter), which is particularly sensitive to the presence of the cosmological constant Λ, or more generally, a component of the cosmological energy contents which has negative pressure, let us call it Q, with an equation of state $p = w\rho$ ($w < 0$). The ideas presented here have been considered by several groups recently (Croft 1998, Seljak 1998, McDonald & Miralda-Escudé 1998, Hui, Stebbins & Burles 1998). AP observed that an object placed at a cosmological distance would have a definite relationship between its angular and redshift extents, which is cosmology-dependent. Consider an object with mean redshift z, and angular size θ. Its transverse extent in velocity units is

$$u_\perp(\theta) = \frac{H}{1+z} D_A(z)\theta \; . \qquad (5)$$

Here H is the Hubble parameter at redshift z, and $D_A(z)$ is the angular diameter distance (Weinberg 1972). For spherical objects the radial and transverse extents are equal, but more generally if the object is squashed radially by a factor α_s, the radial extent is $u_\parallel \equiv \frac{c\Delta z}{1+z} = \alpha_s u_\perp$. Here c is the speed of light and $u_\perp$, $u_\parallel \ll c$ is assumed. This parameter $u_\perp/\theta$ depends on all the different cosmological density parameters Ω_m (matter), Ω_k (curvature) and Ω_Q (Q), but is particularly sensitive to Ω_Q. It is significantly lower for a Q-dominated universe (for $w \lesssim -1/3$) than for a no-Q-universe. (see Fig. 1 of Hui et al. 1998) Qualitatively, one can understand this as follows. In a Q-dominated universe, it is well known that a significantly larger radial-comoving-volume is associated with a given redshift range Δz, compared to a no-Q-universe i.e. $c\Delta z/H(z)$ is larger for a Q-dominated universe. Hence, the angular-extent of a spherical object of a given redshift-extent Δz, would appear to be larger for a Q-universe: $\theta = c\Delta z/H(z)/D_A(z)$ would be larger i.e. a smaller $u_\perp(\theta)$. It turns out for an open universe with no Q, $H(z)$ and $D_A(z)$ roughly balance each other to make $u_\perp(\theta)$ similar to that of a flat-no-Q-universe.

In the case of the Lyα forest, the "object" to use is the two-point correlation function, whose "shape" (α_s) is not spherical because of redshift-anisotropy induced by peculiar motion. We cannot observe the full three-dimensional correlation directly; instead we can measure the one-dimensional correlation along a line of sight, and the cross-correlation between two close-by lines of sight, or their Fourier counterparts: the auto- and the cross-spectra. A comparison of the two provides a new version of the AP test. More precisely, given the observed transmission power spectrum, one can invert eq. (4) to obtain the mass power spectrum, and then use the following equation to predict the cross-spectrum $P^f_\times$ between two lines of sight with separation θ ($P^f_\times$ is the fourier transform of the cross-correlation between the two lines of sight a and b: $\langle \delta^a_f(0)\delta^b_f(u)\rangle$):

$$P^f_\times(k_\parallel, \theta) = \int_{k_\parallel}^\infty BW(k_\parallel/k, k) \; P^\rho(k) J_0[k_\perp u_\perp(\theta)] kdk \qquad (6)$$

where J_0 is the spherical Bessel function. This prediction is cosmology dependent mainly through the parameter $u_\perp(\theta)$, and also through the distortion kernel $W(k_\parallel/k, k)$. The latter generally depends on an effective bias parameter (Hui 1998), aside from the cosmological density parameters of interests, which can fortunately be determined from simulations because the exact "biasing relation between density and the observable (the transmission) is known (eq. [1]), unlike in the case of galaxies (where the AP test has been contemplated by other authors). A comparison of the predicted with the observed cross-spectra, for a given observed auto-spectrum, provides a version of the AP test: assuming the wrong cosmology will result in a wrong prediction for the cross-spectrum. Note that in this test, there is no need to fix the constant B because it enters into the auto- and cross-spectra in the same way.

According to Hui et al. (1998), to reach a $4-\sigma$ level discrimination between e.g. the $\Omega_m = 0.3$ - $\Omega_k = 0.7$ universe and the $\Omega_m = 0.3$ - $\Omega_\Lambda = 0.7$ universe, only 25 pairs of quasar spectra, at angular separations $0.5' - 2'$, would be required. There are roughly 10 such pairs of quasars with existing spectra at the above angular separations, or slightly larger, and at $z \gtrsim 1$ (see e.g. Crotts & Fang 1998 & ref. therein). Upcoming surveys such as the AAT 2dF and SDSS are expected to increase this number by at least an order of magnitude, and to higher redshifts.

4 Tests and More

The cosmological utility of the (low column density) forest relies very much on the simple relation between the optical depth or transmission and the density+velocity fields, which arises from the fact that **I.** the distribution of the latter is determined by gravitational instability alone on large scales, and by baryon-smoothing on small scales (e.g. explosions do not play an important dynamical role); **II.** the ionizing background J does not have significant spatial fluctuations on scales of interest (see §3.2). Here, we loosely refer to this whole set of assumptions as the smooth-fluctuation-paradigm. The ability of most current simulation-inspired work on the forest, which makes use of the above assumptions, to explain the observed b and column-density distributions should be counted as a vindication of the paradigm. After all, this body of work is based on structure formation models constructed to match observations other than those of the forest. Moreover, there are theoretical reasons to believe that J fluctuations should be small on the scales we are interested in (e.g. Croft et al. 1998b). Nonetheless, it is important that we find alternative ways to test our assumptions observationally, as we continue to look for new applications of the forest in cosmology.

Here, we discuss three possible tests that involve only the forest, and one cross-test with another high redshift observation.

I. Use double (or multiple) lines of sight. There are in fact two different tests here. First, for quasar pairs that are very close together e.g. lensed pairs, one can check whether the cross-correlation between the forest in the two lines of sight is as strong as one would expect based on the smooth-fluctuation-paradigm. More specifically, for lensed quasar pairs which are typically of the order of arc-second separation, the distance between the two lines of sight is sub-kpc, which is much smaller than the baryon-smoothing-scale expected for a gas of $T \sim 10^4 K$. This means one expects 100% correlation between these two lines of sight through the forest. Exactly such a behavior has been observed by Rauch (1997). This shows there is no fluctuation in the ionizing background, nor is there complicated motion in the forest due to explosions, at least on these small scales. For quasar-spectra at larger separations, on the other hand, assuming a given set of Ω's, one can turn the procedure in §3.3 around, and test for the redshift-anisotropy due to peculiar motion. This is a robust prediction of gravitational instability. Any other source of fluctuations, such as that due to a fluctuating background, will act as additional sources of "biasing", and change the prediction for the redshift-anisotropy.

II. Use higher order statistics. It is well known that gravitational instability gives robust predictions for higher order statistics such as the skewness $\langle\delta^3\rangle/\langle\delta^2\rangle$ (Peebles 1980), where δ is the overdensity in mass. Just as in the case of galaxies, where measuring the skewness for the galaxy distribution ($\langle\delta_g^3\rangle/\langle\delta_g^2\rangle$ where δ_g is the galaxy overdensity) provides information on the biasing relation between mass and galaxy distributions, measuring the skewness of the transmission should provide a test of the "biasing" relation between transmission and mass density (eq. [1]). Any additional complication due to say a fluctuating ionizing background is going to change that relation and hence the prediction for the higher moments. Efforts are under way to calculate these quantities. As far as measurements are concerned, it is important to guard against possible estimation-biases (Hui & Gaztañaga 1998). It might also well be the case that other higher order measures are better suited for the purpose at hand, because of the particular highly non-linear transformation from density to transmission we have here (especially the exponentiation: $\exp(-\tau)$).

III. If supernova explosions play an important role in the distribution of the gas that makes up the forest, we should be able to see their remnants: metals. Clever efforts to detect metals in $N_{\rm HI} < 10^{14}{\rm cm}^{-2}$ forest have so far only yielded upper limits (see Lu et al. 1998). However, a carbon-to-hydrogen ratio of the order of $10^{-2.5}$ has been detected in systems with $N_{\rm HI} \sim 10^{14.5}{\rm cm}^{-2}$. It is unclear, though, what the corresponding volume-filling factor of these slightly-metal-enriched regions is. This aspect of the forest certainly deserves closer scrutiny. [3]

Finally, it is appropriate at this conference to make some connection with another probe of the high-redshift universe: the Lyman-break-galaxy survey (Steidel et al. 1998). As noted by several authors (Nusser & Haehnelt 1998, McDonald & Miralda-Escudé 1998, Croft et al. 1998), information obtained from the Lyman-alpha forest can be fruitfully combined with observations of the Lyman-break objects, which are observed at similar redshifts ($z \sim 3$). For instance, once the mass power spectrum is inferred from the forest, a comparison with the clustering of the Lyman-break objects would immediately yield a measure of the bias of the Lyman-break galaxies. On the other hand, the bias of the Lyman-break galaxies can be obtained from observations of the Lyman-break objects themselves: either by a direct measurement of their masses (using high resolution infrared observations, which should be feasible in the near future), or by measuring the skewness of the galaxy-distribution. Note that to deduce from either quantity the bias (as defined by the square root of the ratio of the galaxy power spectrum to mass power spectrum), one needs a model for how these galaxies form i.e. how they are formed in relation to dark matter halos (Mo et al. 1998).

With the above information in hand, we have two independent measures of the mass power spectrum at $z \sim 3$, one from the Lyα forest, the other from the Lyman-break-objects making use of the deduced bias parameter. They probe the clustering at different scales, and so one can use them to constrain the shape of the power spectrum; or, if one assumes a particular cosmological model with a definite power spectrum shape, one can test for consistency. Moreover, the latter approach also allows two independent measurements of Ω_m (with minor dependence on the other parameters), by comparison with the cluster-normalized mass power spectrum today (see e.g. Giavalisco et al. 1998, Adelberger et al. 1998, Weinberg 1998). Investigations along these lines are being pursued.

[3] Note added after conference: Cowie & Songaila (1998) recently reported results that are in apparent contradiction with Lu et al. (1998). If the results hold up, this implies some amount of star formation occured at early times, but has stopped by $z \sim 3$ in order not to violate point **I** above. Its impact on the forest remains to be investigated.

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